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A search of UARS data for ozone depletions caused by the highly relativistic electron precipitation events of May 1992

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Abstract. Highly relativistic electron precipitation (HRE) events containing significant fluxes of electrons with $E > 1$ MeV have been predicted by models to deplete mesospheric ozone. For the electron fluxes measured during the great HRE of May 1992, depletions were predicted to occur between altitudes of 55 and 80 km, where HO_x reactions cause a local minimum in the ozone number density and mixing ratio. Measurements of the precipitating electron fluxes by the particle environment monitor (PEM) tend to underestimate their intensity; thus the predictions of ozone depletion should be considered an estimate of a lower limit. Since the horizontal distribution of the electron precipitation follows the terrestrial magnetic field, it would show a distinct boundary equatorward of the $L = 3$ magnetic shell and be readily distinguished from material that was not affected by the HRE precipitation. To search for possible ozone depletion effects, we have analyzed data from the cryogenic limb array etalon spectrometer and microwave limb sounder instruments on UARS for the above HRE. A simplified diurnal model is proposed to understand the ozone data from UARS, also illustrating the limitations of the UARS instruments for seeing the ozone depletions caused by the HRE events. This diurnal analysis limits the relative ozone depletion at around 60 km altitude to values of <10% during the very intense May 1992 event, consistent with our prediction using an improved Goddard Space Flight Center two-dimensional model.

1. Introduction

It has been argued that highly relativistic electron precipitation (HRE) events containing significant electron fluxes above 1 MeV should deplete ozone in the lower mesosphere by inducing chemical changes in excess of the usual diurnal variations [*Baker et al.*, 1986; *Goldberg et al.*, 1994, 1995a, b]. Since HREs can sustain their activity for several days, recur over several solar rotations, and cover a broader region in longitude and latitude than the auroral zone, their impact on the middle atmosphere could be large. On the basis of satellite data observed at geosynchronous orbit, HRE events are most pronounced during the declining phase of the solar cycle, increasing in intensity, spectral hardness, and frequency of occurrence as the solar cycle reaches minimum [*Baker et al.*, 1979, 1986, 1987, 1993]. From comparisons with lower-altitude satellites [*Imhof et al.*, 1991], and from a rocket study of a modest HRE, it is apparent that a significant fraction of the outer zone electrons associated with an HRE reach the middle atmosphere [*Herrero et al.*, 1991; *Baker et al.*, 1993] and strongly influence the electrodynamics and composition (e.g., O_3 and OH) of that region [*Goldberg et al.*, 1994, 1995a, b]. Because HREs can be sustained up to several days, their cumulative effect on the high-latitude mesosphere could dominate other particle sources of energy input such as relativistic electron precipitation events and solar proton events.

The expected relative depletion in ozone should peak between 65 and 75 km altitude, where HO_x reactions cause a local minimum in the ozone number density and mixing ratio [*Jackman*, 1991]. The horizontal distribution of the precipitation should track the magnetic field of the Earth, with a sharp boundary equatorward of the $L = 3$ magnetic shell (corresponding to a magnetic latitude of 55°; see Figure 1.) As the terrestrial magnetic field is tilted with respect to the terrestrial rotation axis, any effects governed by the magnetic field will also be tilted. On the basis of the predicted dependence of the ozone depletion with altitude and mag-

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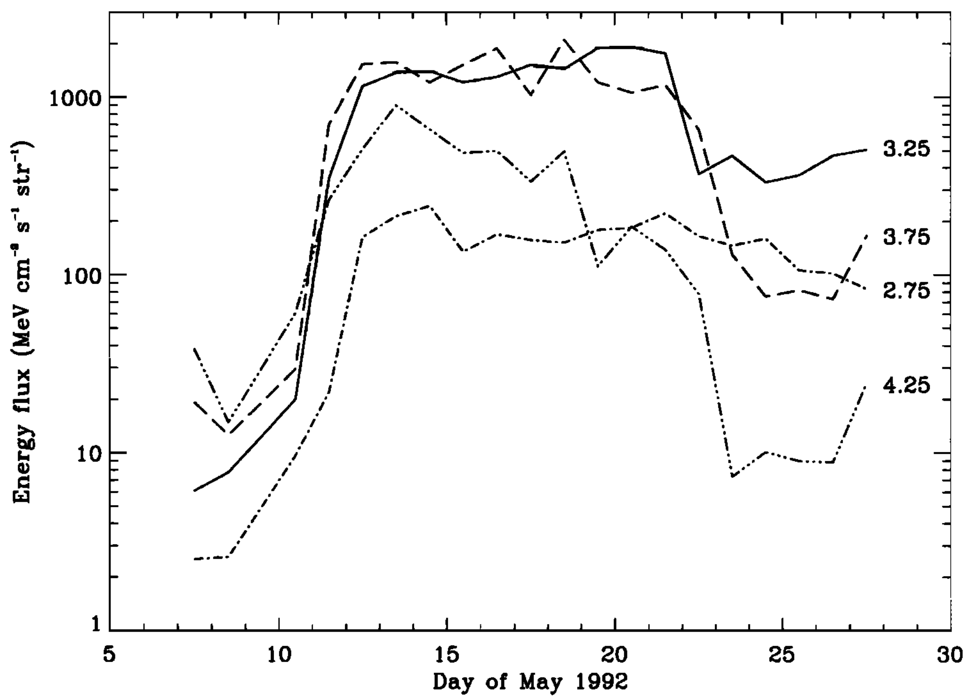

Figure 1. Day-averaged precipitating electron energy fluxes for May 1992 from the Particle Environment Monitor. Counts were summed over energy bins with $E > 1$ MeV and binned into L shells with widths $\Delta L = 0.5$.

netic coordinates as given by observations of the electron flux by the PEM instrument, we have searched for the signature of such an event in ozone data from the cryogenic limb array etalon spectrometer (CLAES) and microwave limb sounder (MLS) on UARS.

The ozone data analysis is complicated by the presence of a strong diurnal cycle and noise in the data inversion that grows with altitude; thus small depletions may not be observable with the MLS or CLAES data. Using data from May 1992, the most intense HRE observed during the first 4 years of UARS observation, displayed against local solar time (LST), we expected the depletions to be strong functions of the LST values sampled between May 11 and May 21. Median values over 15 min LST bins and Fourier fits in LST were used to try to extract the anticipated depletion signal. Results of this analysis are reported here.

2. UARS Particle Measurements From PEM

Surveys by the PEM High Energy Spectrometer (HEPS) team have determined that, from the launch of UARS through 1994, the relativistic electron fluxes of May 1992 were the most intense and most energetic of the events seen by UARS [*Gaines et al.*, 1995]. Within the belt of magnetic L shell $3 \leq L \leq 4$ (or magnetic latitudes between 55° and 60°) the locally precipitating HRE flux reached a large value on May 11 and continued at this value until May 21 (see Figure 1). It then decreased by a factor of about 8 in magnitude and continued through May 27. Precipitating electrons with $E > 1$ MeV extended to magnetic latitudes lower than those for other events. Compared to background effects for magnetically undisturbed times and locations, the energy deposition rate into the lower mesosphere increased at least 100 times during this HRE event.

The UARS Particle Environment Monitor investigation's High Energy Particle Spectrometers (HEPS) provide energy- and pitch-angle-resolved measurements of the low altitude electron flux to 5 MeV [*Winningham et al.*, 1993]. For the analysis reported in this paper the angular measurements are used to distinguish electron fluxes that are stably trapped (in the region where they are being measured, at least) from those that will directly precipitate into the atmosphere. The latter component is found in the angular range with respect to the magnetic field that corresponds to the bounce loss cone (BLC).

The HEPS measurements are used conservatively in this analysis by counting BLC flux measurements only when the full angular range of a sensor is within the BLC. If the mechanism causing the electron precipitation is dominated by small angle scattering, this procedure can lead to underestimates of the total precipitated flux because it tends to bias against measurements at the edge of the BLC, where the flux would be more intense [*Imhof and Gaines*, 1993]. Thus the estimates of the decrease in ozone due to these electrons are lower limits. A larger decrease would not necessarily be inconsistent with these predictions.

The direct measurement of the precipitating electron flux at low altitude provided by HEPS is more reliable than estimates based on measurements from, for example, geosynchronous satellites, or on other scaling from total electron flux measurements. As shown by *Gaines et al.* [1995], temporal variations in the electrons flux intensity and their energy distributions can vary signif-

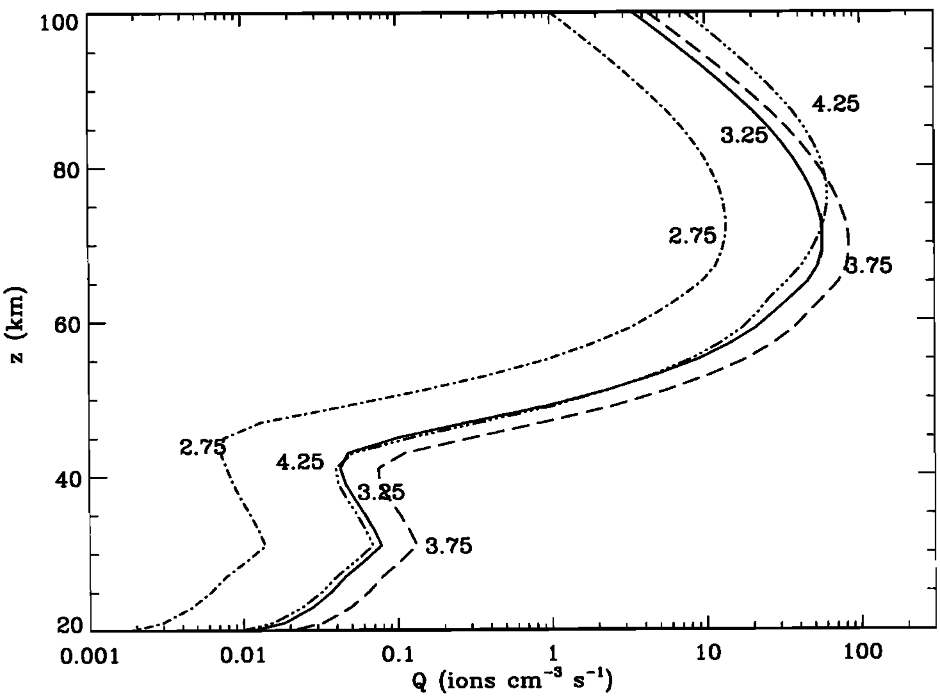

Figure 2. Ion production rates as a function of altitude and magnetic shell for the precipitating electron fluxes of May 12, 1992. The fluxes were averaged over the day and L shells.

icantly between the trapped and precipitating components. In this paper the electron fluxes are presented as daily averages. Such a procedure tends to average out small-scale variations in space or time, but at the energies considered here the diurnal variations are reduced in amplitude [*Vampola and Gorney*, 1983]. We believe that this consideration is most appropriate for our study, recognizing that locally and on small scales, larger effects might be observable.

From the measured precipitating electron energy spectrum we have derived the energy deposition height profiles, using techniques of *Goldberg et al.* [1984]. On May 12, 1992, a typical day in the HRE event under study, Figure 2 shows mean values of the ion pair production rate (Q) profiles for bands of $L = \langle L \rangle \pm 1/2$. We found that the zone of maximum energy deposition was centered about $L = 3.75$. From these profiles it is apparent that large quantities of ions are produced down to 50 km [cf. *Goldberg et al.*, 1994], far deeper than those produced during other kinds of electron precipitation events.

3. Predicted Loss of Ozone Due to Electron Precipitation

Above altitudes of 50 km the chemical lifetime of ozone is less than 1 day, causing a strong diurnal cycle to appear in the measured data, with a higher ozone mixing ratio at night than during the day. These diurnal variations in mesospheric ozone are driven by photochemistry and catalytic reactions. Atomic oxygen produced by photodissociation of molecular oxygen combines with O_2 to form ozone in the absence of sunlight. HO_x compounds, the major catalytic reactant in the mesosphere, are produced by photolysis and oxidation of water vapor in the undisturbed mesosphere. The change from day to night values is extremely rapid, so that the diurnal cycle resembles a square wave, centered at noon, with some structure due to other competing reactions [*Allen et al.*, 1984]. UARS MLS data from midlatitudes are consistent with the diurnal models [*Ricaud et al.*, 1996]. A schematic of a diurnal cycle is shown in Figure 3. Day and night values of ozone, as well as the LST cycle length, were taken from MLS measurements at 59 km during May 1992.

We employ the Goddard Space Flight Center two-dimensional chemistry and transport model (GSFC-2D) [e.g., *Jackman et al.*, 1996] to study the influence of HREs on mesospheric ozone. This model has been used before to study charged particle effects on ozone from solar proton events [*Jackman*, 1991; *Jackman et al.*, 1990, 1996] and HREs [*Goldberg et al.*, 1995a]. The model computes daytime average values rather than diurnal cycles of constituents. The results of the model are thus most appropriate for long-term (hours to days) particle precipitation events, such as the HREs that occurred in May 1992.

The production of ions during an HRE event can enhance HO_x compounds through complicated ion chemistry [*Solomon et al.*, 1981, 1983]. These HO_x constituents can then affect the ozone concentration during the particle event. Approximately two HO_x species are produced from each ion pair up to about 70 km. However, above 70 km, the production of HO_x species from each ion pair has a strong dependence on the ionization rate and the duration of the particle precipitation event [*Solomon et al.*, 1981]. We use the production of HO_x constituents per ion pair as a function of altitude from

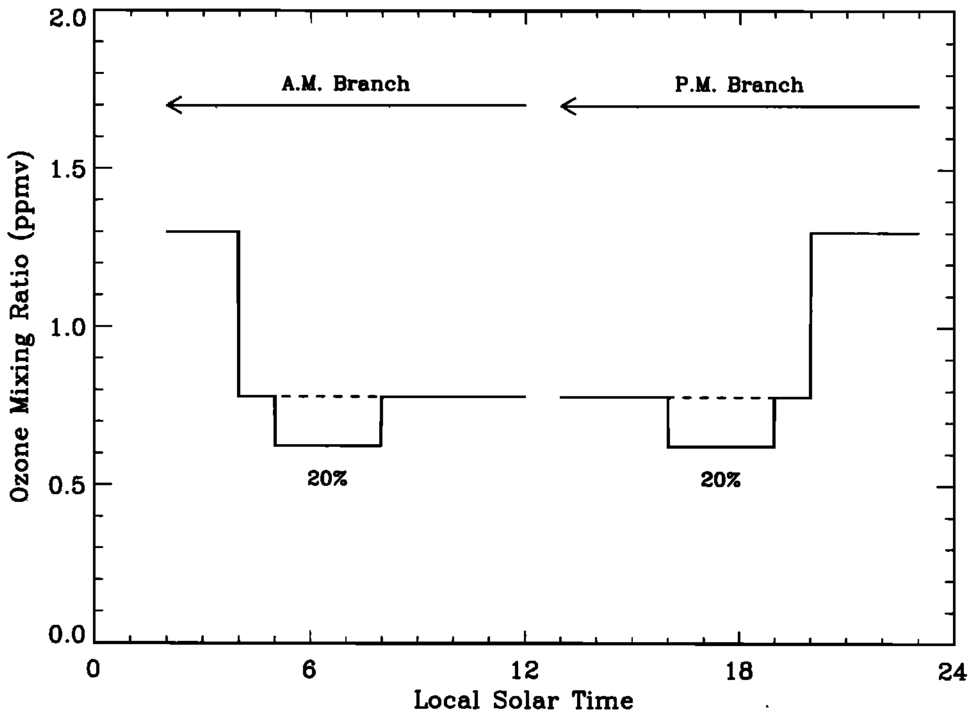

Figure 3. Simplified diurnal cycle of ozone at 59 km. Data from the Microwave Limb Sounder (MLS) was used to derive values of the ozone mixing ratio near midnight and noon, as well as the location of the dawn and dusk terminators. The solid line shows how a 20% decrease in ozone by a highly relativistic electron (HRE) event would be seen by MLS or the Cryogenic Limb Array Etalon Spectrometer (CLAES); the dashed line shows the unperturbed ozone.

Figure 2 of *Solomon et al.* [1981] for ionization rates of 50 $cm^{-3}\ s^{-1}$ (similar to the ionization rates for $L = 3.75$ from May 12, 1992) in our model calculations.

The HO_x constituents vary over the course of the day and are a strong function of their production. The background source of HO_x is very dependent on the ambient H_2O amount and sunlight (and thus solar zenith angle and LST) through the photolysis of H_2O and the reaction of $O(^1D)$ with H_2O. The H_2O in the 2-D model is computed self-consistently and is in reasonable agreement with Halogen Occultation Experiment (HALOE) measurements in the mesosphere [*Chandra et al.*, 1997].

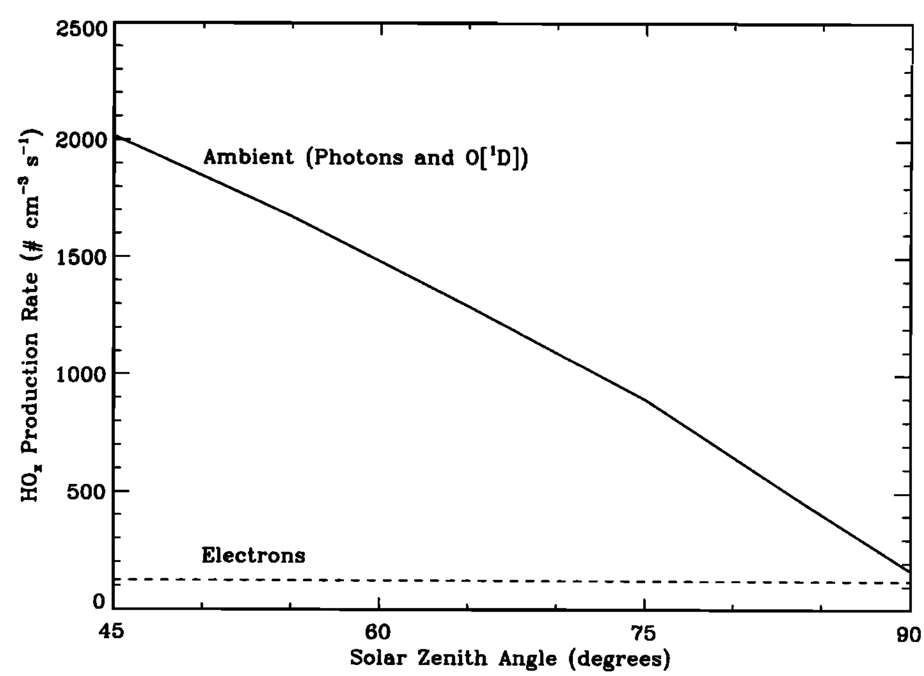

Figure 4. HO_x production ($cm^{-3}\ s^{-1}$) as a function of solar zenith angle for the ambient atmosphere (solid line) and the HRE for $L = 3.75$ on May 12, 1992 (dashed line), at 0.04 mbar (~70 km).

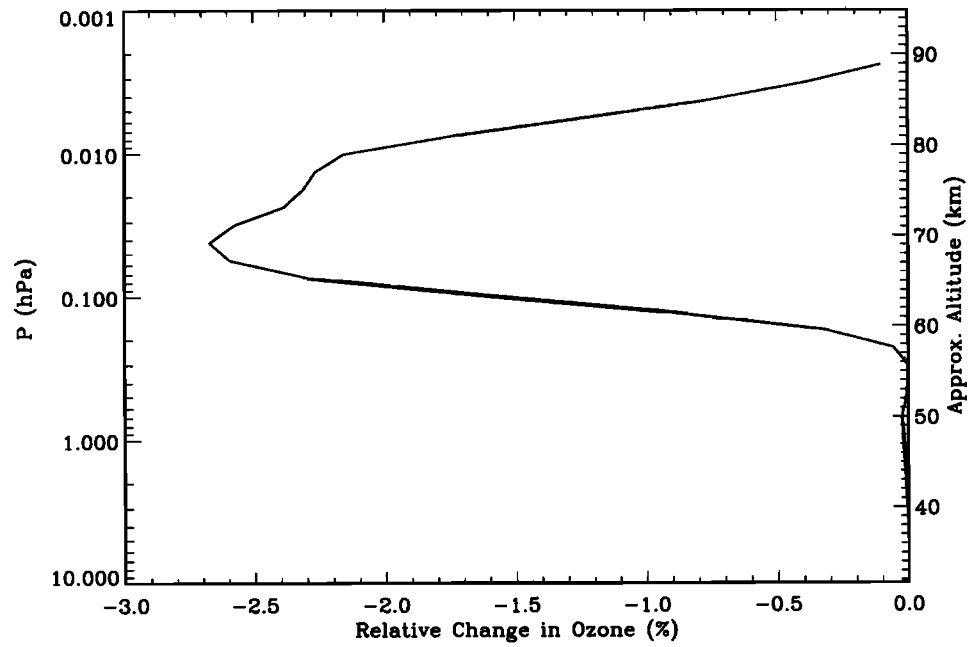

Figure 5. Predicted relative ozone depletion using the model of *Jackman et al.* [1996]. The percentage change in ozone due to the HREs is computed by the relative change of a model run including the May 12 HRE-induced ions from another model run without the HRE flux.

The background amount of HO_x production at 65°N on May 12, 1992 in our model is computed at 0.04 mbar (~ 70 km) to range from about 2000 cm^{-3} s^{-1} at 45° solar zenith angle (about noon LST) to 170 cm^{-3} s^{-1} at 90° solar zenith angle (see solid line in Figure 4).

The HRE source of HO_x is assumed to be independent of solar zenith angle (SZA), and thus there is expected to be a large SZA influence in the simulated particle effects. This large SZA effect has been measured and modeled previously for solar proton events [e.g., *Thomas et al.*, 1983; *Solomon et al.*, 1983; *McPeters and Jackman*, 1985; *Jackman and McPeters*, 1985; 1987]. The HRE source at 0.04 mbar (~70 km) for $L = 3.75$ for May 12, 1992 is computed to be 120 cm^{-3} s^{-1} on May 12, 1992 (see dashed line in Figure 4). This computed HRE source of HO_x is competitive with the background HO_x source at only the very highest SZAs (>80°). Our 2-D model daytime average computation with an average SZA of about 65° has a background HO_x production of 1300 cm^{-3} s^{-1}, over an order of magnitude larger than the HRE source of HO_x.

We input an assumed continuous source of HRE-related HO_x production from the $L = 3.75$ ion production rate curve of May 12, 1992 into our 2-D model at 65°N to predict the ozone change. The HO_x enhancements can lead to ozone depletion through several HO_x catalytic processes. Above 60 km the catalytic cycle

$$\begin{aligned} H + O_3 &\rightarrow OH + O_2 \\ OH + O &\rightarrow H + O_2 \\ \text{Net:}\ O_3 + O &\rightarrow O_2 + O_2 \end{aligned}$$

is very important. Our simulated ozone percentage change due to the HREs is computed by comparing a model run that includes the electron-induced ions calculated with the May 12 HRE flux with another model run without the HRE flux and is presented in Figure 5. The peak computed ozone decrease due to the HRE precipitation is about 2.7% at 0.4 mbar (~ 70 km), a rather small depletion. As we indicated earlier, the precipitating electron flux and ion production rates may be underestimated thus the HO_x production and subsequent associated ozone decrease may also be underestimated. The UARS measurements have been used to help quantify the ozone change and determine whether the May 1992 HREs could be responsible for a significant ozone variation.

4. UARS Ozone Measurements

UARS has a precessing orbit, requiring roughly 34 days to move 12 hours in LST. At the beginning of a yaw cycle, MLS and CLAES begin measuring atmospheric parameters at two values of LST, one near noon and the other near midnight. As the yaw cycle progresses, both branches move to earlier values of LST, reaching midnight and noon just before the turning of the satellite that starts the next yaw cycle. Complete coverage in LST is available for a given latitude band by combining the A.M. and P.M. branches of the orbits observed over a yaw cycle. By sweeping out the diurnal cycle one can see how the HRE event changes the ozone concentration. The cold side of UARS was pointed north during May 1992, so that the ozone measurements are in the same polar region throughout the event.

Six instruments on UARS are capable of measuring the ozone mixing ratio. This capability allows for validation of each instrument with the others as well as permitting a comparison of the various observing techniques that can be used [*Cunnold et al.*, 1996]. MLS and CLAES are two instruments that were optimized to measure the abundances of minor gas species in the stratosphere—where chemical lifetimes typically exceed 1 day and values show minimal fluctuations, permitting zonal averages to be used. In this work we concentrated on ozone data from CLAES and MLS.

MLS measures thermal emission due to ozone in the microwave band at 184.4 GHz [*Barath et al.*, 1993]. The ozone concentration was derived from the observed radiances by an inversion technique. The O_2 line used for pressure alignment is sensitive to the Earth's magnetic field and the inversion becomes increasingly less accurate above 0.215 hPa (59 km) [*Froidevaux et al.*, 1996]. CLAES used infrared lines of ozone for a similar inversion [*Roche et al.*, 1993; *Bailey et al.*, 1996]. This instrument had a fixed altitude sampling tied to the National Meteorological Center (NMC) model at the lowest altitude. The uppermost altitude point is roughly 59 km, although a limited number of higher-altitude measurements are available in the database. As a result of these limitations we concentrated on data at UARS level 22, roughly 59 km. The time-ordered, level 3 (3AT) form of the ozone data was obtained from the UARS data archives at the Goddard Space Flight Center.

There are several restrictions on the UARS data that complicate the detection of HRE ozone depletions. First is the averaged geographic coverage. The specified location of the 3AT data is based on an average over a UARS minute of roughly 65 s. A 400 km footprint is assigned to each 3AT profile, giving two points per orbit in the $L = 3-4$ region (corresponding to magnetic latitudes between 55° and 60°), one each in the A.M. and P.M. branches. This is similar to the width of the region being irradiated with energetic electrons. The sharp boundary of the HRE flux implies that some samples of the mesospheric constituents are only partially irradiated by the electron flux. This averaging tends to increase the value of the ozone mixing ratio in a particular profile.

5. Local Solar Time Analysis

To measure deviations from normal ozone concentrations caused by HRE events, we must first accurately account for the natural variation of ozone. In the mesosphere this requires measuring the deviation from the diurnal cycle (see section 3). We expected the ozone depletions by HREs to follow the Earth's magnetic field and selected data with L values between 3 and 4. Values of the ozone mixing ratio were then plotted as a function of LST, as in Figure 6, where the MLS ozone mixing ratio for May 5–29, 1992, with geographic locations with $3 \leq L \leq 4$, and at UARS altitude level 22 (59 km using the approximate equation: altitude z = level $\times$ 8/3 km) are shown. The noise level is considerable, estimated to be 0.17 ppmv on a mean of 0.94 ppmv (see Table 1). In Figure 6, points drawn with plus symbols were observed during the HRE event, while points with open squares were measured before, and those with diamonds were measured after the event. Although the overall diurnal cycle is similar to that of Figure 3, there is no apparent decrease of ozone during the HRE event. CLAES data taken with the blocker 9 channel for similar conditions have a noise level of 0.24 ppmv and are shown in Figure 7. As Table 1 shows, MLS and CLAES agree on the average magnitude of the O_3 mixing ratio at 59 km, but CLAES has slightly larger dispersions about the diurnal fit. The use of the χ^2 statistic is valid because the data are normally distributed about the fit.

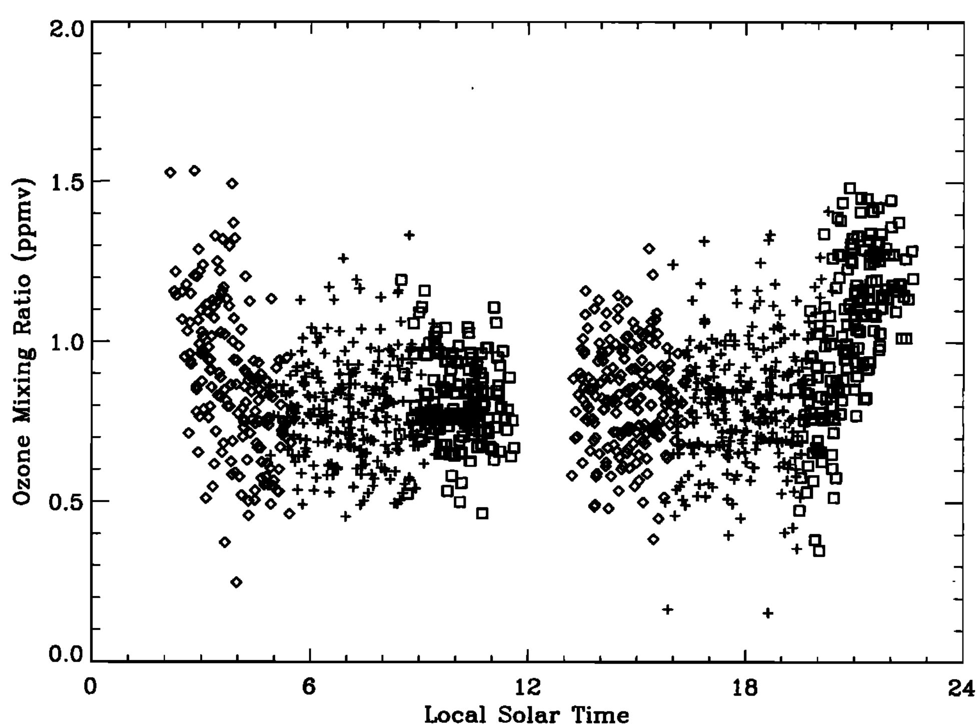

Figure 6. Unfiltered MLS data at 59 km during May 1992. The scatter in the data is determined by the inversion technique used by the MLS team. Error bars for the points would reproduce that scatter.

Table 1. Point-by-Point Ozone at 59 km, May 1992

	Number of Points	Mean, ppmv	σ, ppmv	χ^2
MLS 183 GHz	1117	0.93	0.17	1273
CLAES O3B9	1007	0.98	0.24	1035

To average the data without further mixing undisturbed ozone values with those expected during the HRE event, which would further reduce the strength and significance of the depletion signal, we used low-order Fourier fits and median values within 15 min LST bins. This method is discussed in the next section.

6. Fourier Fits to Simulated and LST-Averaged Data

Simulated ozone mixing ratio data described by a daytime value of $O_{3,\mathrm{day}}$, a nighttime value of $O_{3,\mathrm{night}}$, a sunrise at T_0, and sunset at $24-T_0$, were produced using a high-order Fourier series. Values for these coefficients were taken from MLS data at 59 km, and normally distributed noise was added to the model value with an appropriate σ. To model the HRE event the ozone values were decreased during the appropriate LST limits prior to adding the noise.

Model data through a diurnal cycle were generated by using $T_0 = 4$, $O_{3,\mathrm{day}} = 0.78$ ppmv, and a day to night ratio of 0.6. A value of $\sigma = 0.2$ ppmv was assumed, consistent with the average of values at 59 km for MLS (0.17 ppmv) and CLAES (0.24 ppmv). Our typical computed ozone decreases are some 3% (see section 3); however, it is possible for the ozone depletions to be larger. We used depletions of the ozone by 10–50% between 0500–0800 and 1600–1900 LST to model the effect of the HRE events as they would be seen by a precessing satellite. Points within the $L = 3 - 4$ band do contain some points outside the HRE flux due to the small geographic area of the precipitating region and the averaged horizontal sampling of the 3AT data. In one simulation all of the points in the above time frame were reduced, while another had every other point reduced—mimicking this effect. By depleting every other point we could better simulate the steep equatorward boundary of the HRE events.

Figure 3 shows the simplified diurnal model when a 20% depletion is applied to all points in the 0500–0800 and 1600–1900 LST range. Next, Figure 8 shows the model data sampled with $\sigma = 0.2$ ppmv, along with a seven-partial Fourier fit. With a 20% depletion, decreases are easily identified in the simulated data and the diurnal fit. When every other point in the time series is depleted, the contrast is reduced, and the depletion is not well represented until a 40% depletion is used (not shown here). Residuals of the model data from the diurnal fit are well described by a Gaussian. The correlation coefficient is also consistent with a good fit. We can then determine what limits can be placed on the observability of ozone decreases at these altitudes in the MLS and CLAES data. Roughly speaking, if the ratio $\sigma/O_{3,\mathrm{day}}$ exceeds the relative depletion, the HRE effects will not be visible.

We also searched for a correlated decrease in the A.M. and P.M. branches and an increasing amplitude of the depletion with altitude. To reduce the statistical fluctuations, a median of values in 15 min intervals in LST was

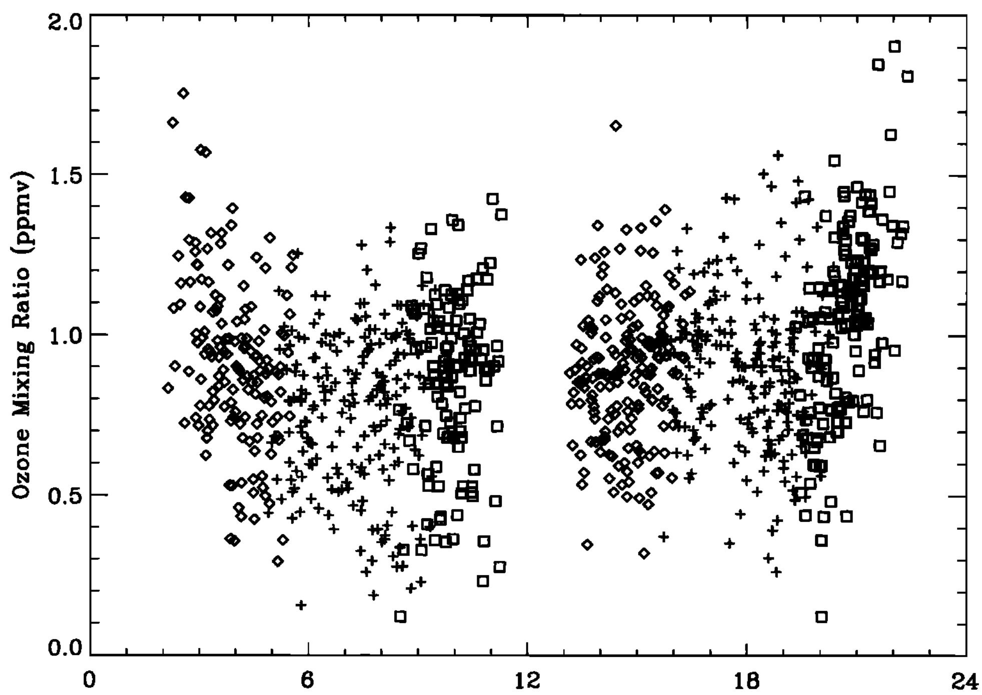

Figure 7. Unfiltered CLAES data at 59 km during May 1992. The scatter in the data is determined by the inversion technique used by the CLAES team. Error bars for the points would reproduce that scatter.

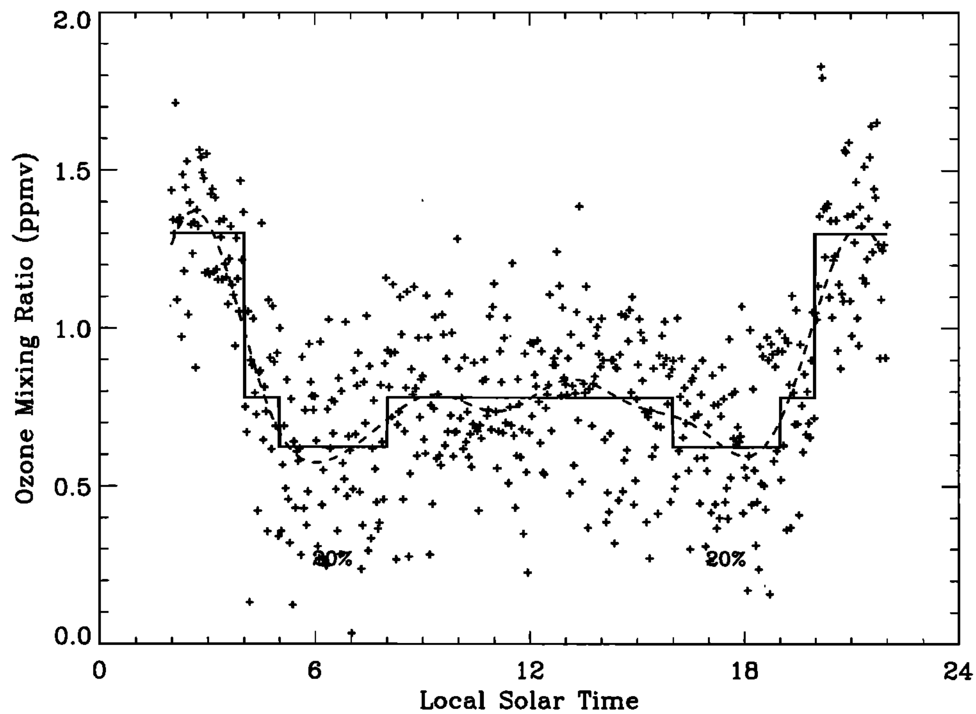

Figure 8. Simulated data with 20% depletion in 0500–0800 and 1600–1900 LST.

used for the analysis (see Table 2). Figure 9 shows the MLS ozone mixing ratio between May 5, 1992, and May 29, 1992, for locations $3 \leq L \leq 4$ and UARS levels 18, 20, and 22 (approximate altitudes of 48, 53, and 59 km, respectively.) Generally speaking, the satellite moves from higher to lower values of LST, starting at 21/11 LST and precessing to the left in each half of the figure. Any effects that change during the month of May will change the variation in the appropriate region of LST. We estimate that the effects of the HRE event should be seen between 1500 and 2000 LST, and 0500–1000 LST. At 48 km, both MLS and CLAES show an apparent semidiurnal variation, with ozone increasing to a local maximum at 0600 LST. This is an expected variation of ozone in the stratosphere during undisturbed periods.

Finally, we have plotted low-order Fourier fits to the binned values minus the average value, for each of the three altitudes (MLS in Figure 10 and CLAES in Figure 11). The region where the HRE flux was active is denoted by a gray rectangle. Neither MLS nor CLAES shows consistent decreases in the A.M. or P.M. branches with altitude. MLS shows an increase of the amplitude of the diurnal cycle as z increases from 48 to 59 km.

7. Summary and Conclusions

Data from MLS and CLAES have been examined for evidence of ozone depletions due to the precipitation

Table 2. Median Value Ozone at 59 km

	Number of Points	Mean, ppmv	σ, ppmv	χ^2
MLS 183 GHz	76	0.941	0.057	11.9
CLAES O3B9	76	1.01	0.038	132

of highly relativistic electrons in May 1992, the most intense and longest lasting HRE observed by UARS between 1991 and 1995. An updated version of the GSFC-2D photochemical model predicted ozone depletions in the mesosphere during this event with a typical amplitude of 2.7% at the highest altitude available in the data. A simplified model of the diurnal cycle of ozone at an altitude of 59 km was used to illustrate two correlations in the data that would emphasize the predicted depletions. Similar relative depletions should have been seen at both values of LST observed during the HRE event. Furthermore, the chemical model predicts that the depletion amplitude should increase with altitude in the lower mesosphere.

Simulated data, described here and analyzed by using the same algorithms as those used in the UARS data, were used to demonstrate how the instrumental noise can mask the signal. Noise levels of the data, relative to the mean value in the daytime, must be less than the relative depletion that is to be observed. This did not happen in the observed data above 60 km. It is possible that the diurnal fit techniques might show depletions in data from instruments that sample the ozone mixing ratio at higher altitudes where the relative depletion is expected to be larger.

Median values in 15 min LST bins were examined with a Fourier fit for correlations of the ozone depletion with altitude and A.M./P.M. branches. At the three altitudes examined, depletions consistent with our schematic diurnal cycle were not found. Fourier analyzing the diurnal variation also gives a more accurate value of the average ozone concentration at mesospheric altitudes. The calculated average includes the effect of the solar-driven daily variation and removes any biases introduced by the duty cycle of the orbital parameters

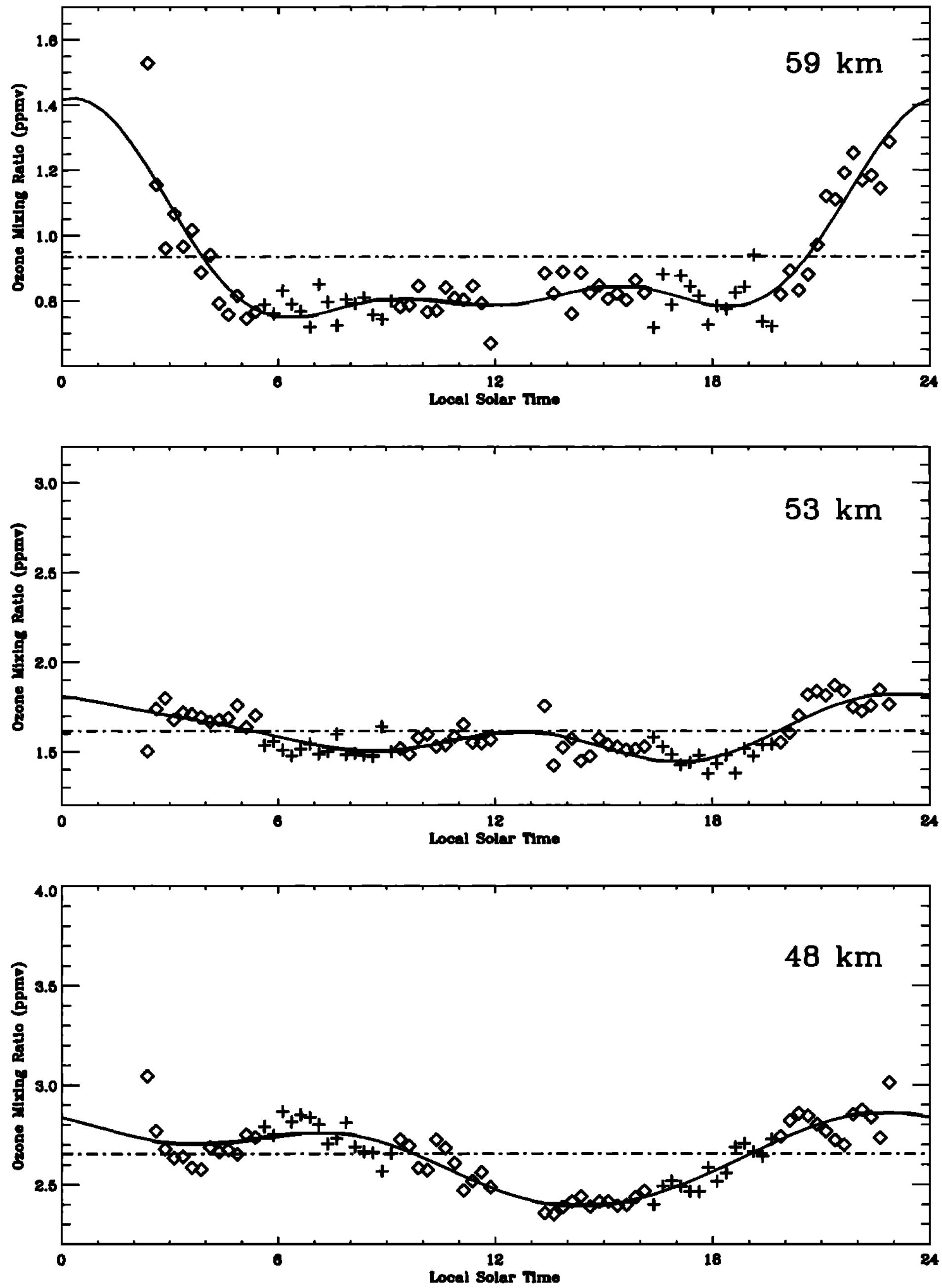

Figure 9. MLS data at three altitudes during May 1992. A median filter of 15 min in LST was used to generate the points.

of UARS. Another study [*Pesnell et al.*, 1997] addressed the variation of mesospheric ozone through equinox.

Precipitating electrons may cause ozone depletions in the mesosphere, but the signal-to-noise ratio at 59 km of CLAES and MLS, which had to be much less than the predicted relative depletion of 3–10%, is not sufficient to measure the effect. A more realistic photochemical model is necessary to refine the predicted magnitude of the depletions. The current model assumes that the signal is constant in time and space for periods larger than a day and areas large compared to the mixing region. Both assumptions need to be examined to understand whether the model is predicting too small or large a change in the mesospheric ozone. Recent measurements of the OH abundance by *Summers et al.* [1997] indicate that the model predictions of the abundance of OH are too large. If this indication can be interpreted as a loss rate for ozone by HO_x constituents that is larger than has been assumed in the models, the predicted ozone depletion due to HRE events will also be smaller. Also, the predicted ozone depletions are sensitive to the water vapor concentration, with an increasing water vapor content leading to a decreased relative ozone depletion.

Although we have analyzed the most intense and longest lasting HRE event seen by UARS, we found no measurable effect on ozone in the upper stratosphere

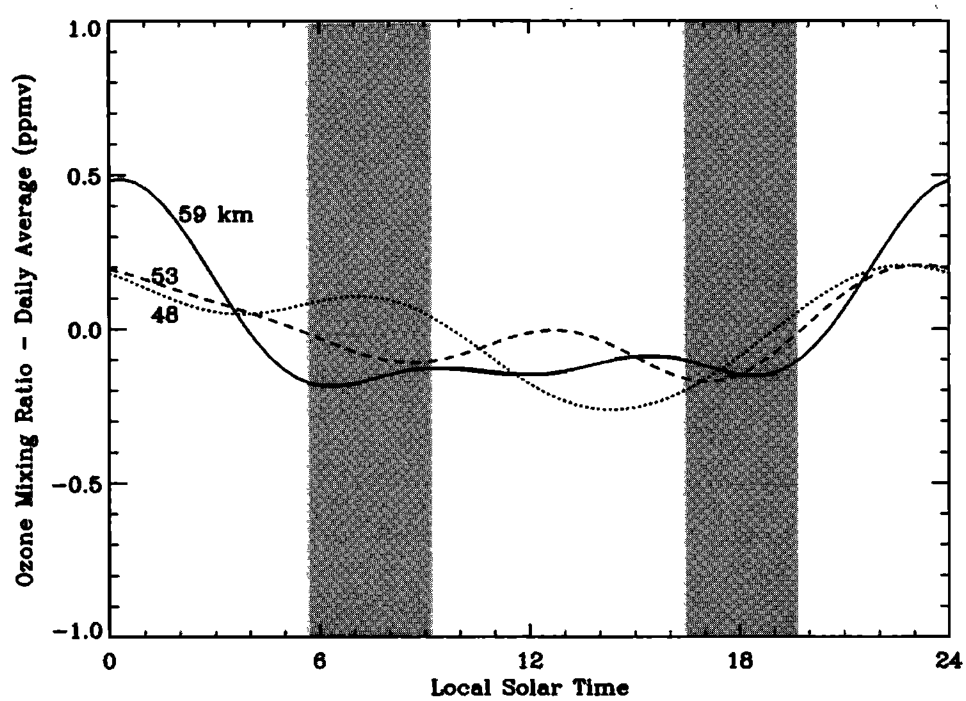

Figure 10. A comparison of the diurnal fits for the MLS ozone data in Figure 8. The average value of ozone was subtracted from each value of the mixing ratio to allow comparisons of the different altitudes.

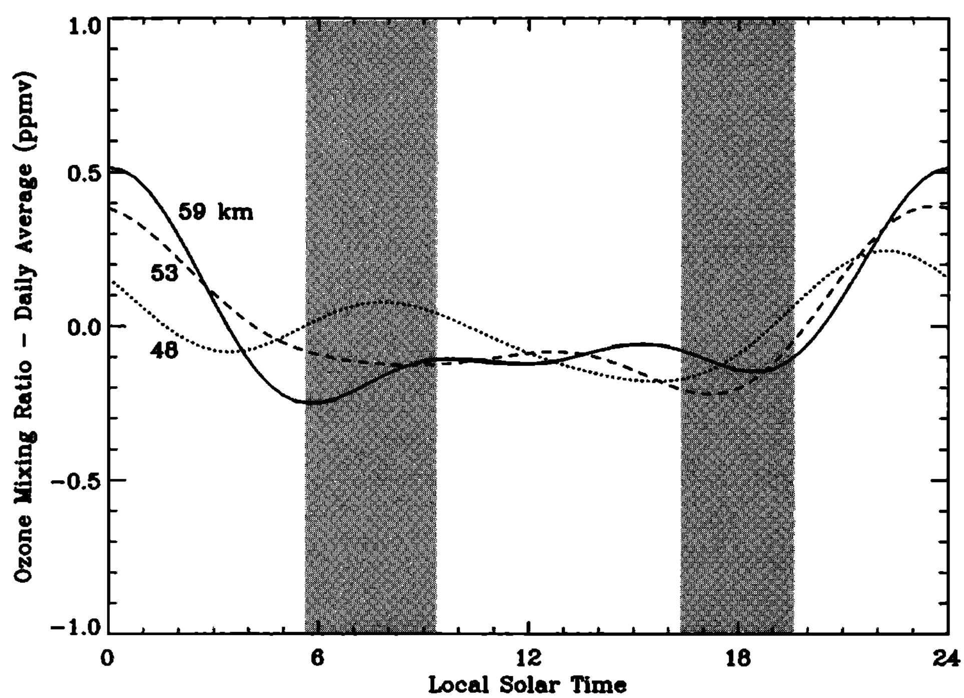

Figure 11. A comparison of the diurnal fits for the CLAES ozone data. The average value of ozone was subtracted from each value of the mixing ratio to allow comparisons of the different altitudes.

and lower mesosphere. Without a consistent, measurable effect these results cast doubt on the significance of the effect that highly relativistic electrons have on the overall budget of ozone in the upper atmosphere.

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